Chemical and Petroleum Engineering, Vol. 44, Nos. 7–8, 2008

INDUSTRIAL ECOLOGY

CHOICE OF HEAT ENGINE CHARACTERISTICS FOR BURNING BIOGAS IN SOLID DOMESTIC WASTE DUMPS

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It is demonstrated that as an alternative source of energy it is possible to use biogas, formed in dumps for burying solid domestic waste (SDW). Heating cycles are studied for utilizing biogas in SDW dumps. T–ΔS-diagrams are constructed for calculated cycles (Otto, Trinkler, Diesel) for model mixtures (CH_4–CO_2–air) and for the actual composition of a biogas sample taken at different depths from the body of the dump. It is established that the most ecologically safe installation for utilizing biogas is a heat engine operating by a Diesel cycle.

As an alternative source of energy it is possible to use biogas, formed in dumps for burying solid domestic waste (SDW), as a working medium for heat engines (HE). However, in biogas there are chemically active dangerous components of the 3rd class of toxicity with a concentration many times exceeding standard values [1]. During combustion of biogas, as a result of chemical reactions in the combustion products such dangerous compounds form. Use of devices for flameless gas combustion does not change the thermochemical conditions for occurrence of reactions. As is well known, there is a change in flame gas dynamics since diffusion combustion in the flame front changes into a process of volumetric combustion with small scale turbulence. These experimentally confirmed facts [2] give rise to a requirement for using at the inlet of a HE a system of gas cleaning structures on whose functioning it is necessary to expend part of the energy obtained in the same HE.

In addition, in order to provide combustion stability it is necessary at the expense of energy, generated by the HE, previously to dry biogas, and with the use of a gas turbine unit even to compress it. Previous calculations, performed for the results of experimental studies of dump gas before and after combustion [3], have shown that its thermodynamic properties, including calorific value and self-ignition temperature, differ markedly from the same properties for methane–air–carbon dioxide mixtures. Considering that the aim of thermal utilization of biogas in dumps is not only improvement of the ecological situation in the area of their location, but also to obtain the maximum useful work, it is necessary to compare the HE thermodynamic cycle distinguished by the method of heat supply: a Diesel cycle at constant pressure, a Trinkler cycle, i.e., mixed; an Otto cycle with constant volume; a Brighton cycle with constant pressure.

In order to obtain reliable calculated results, samples of biogas were taken from an SDW dump (Table 1) by the procedure in [3]. As follows from Table 1, the methane concentration in samples increases with an increase in H of gas sampling depth from the body of the dump. In calculations, there was also consideration of thermophysical and thermochemical properties detected in experiments [1] during combustion of dump biogas for strictly standard compounds of the 2nd and 3rd classes of toxicity, and also polychlorinated biphenyls, within whose composition there are compounds of the dioxin homologous series (Table 2).

Moscow State University of Engineering Ecology (MGUIE). Translated from Khimicheskoe i Neftegazovoe Mashinostroenie, No. 7, pp. 36–38, July, 2008.

0009-2355/08/0708-0399

TABLE 1

H, m	Biogas component concentration, mg/m^3									
	Dust	C_xH_y	NO_2	H_2S	SO_2	CO	Benzene	Toluene	Ethylbenzene	Xylenes
0	10.26	1.83	0.02	0.005	0.05	1.0	0.35	0.14	0.12	0.06
0.4	14.31	4.43	–	–	–	1.75	0.06	0.02	0.02	0.01
1.0	15.8	5.6	–	–	–	2.3	0.02	0.01	–	–
2.0	17.2	8.3	–	–	–	3.1	–	–	–	–
10	21.1	10.1	–	–	–	2.2	–	–	–	–
MPC	0.5	1.0	0.085	0.008	0.5	0.5	1.5	0.6	0.02	0.2

TABLE 2

H, m	Biogas combustion products concentration, mg/m^3													
	Dust	C_xH_y	NO_2	H_2S	SO_2	CO	Benzene	Toluene	Ethylbenzene	Xylenes	p, m-xylenes	o-xylenes	PCB	HCl
0	8.48	3.41	0.17	0.027	0.65	7.4	1.67	0.84	0.6	0.13	0.11	0.02	2.7	0.1
0.4	12.1	4.43	–	–	–	9.5	1.86	0.92	–	–	–	0.02	2.9	0.4
1.0	14.5	6.23	–	–	–	10.3	2.12	1.01	–	–	–	0.01	3.2	0.7
2.0	15.6	7.6	–	–	–	11.2	–	–	–	–	–	–	4.1	0.9
10	19.3	11.1	–	–	–	11.6	–	–	–	–	–	–	4.5	1.1
MPC	0.5	1.0	0.085	0.008	0.5	0.5	1.5	0.6	0.02	0.2	–	–	0.5	1.0

TABLE 3

Cycle	Main parameter
Diesel	$\varepsilon = V_1/V_2 = 20$
	$\rho = V_4/V_3 = 1.5$
Trinkler	$\varepsilon = V_1/V_2 = 15$
	$\lambda = p_3/p_2 = 1.2$
	$\rho = V_4/V_3 = 1.5$
Otto	$\varepsilon = V_1/V_2 = 8.0$
	$\lambda = p_3/p_2 = p_4/p_2 = 1.5$
Brighton	$\varepsilon = V_1/V_2 = 6; 10; 20$
	$\rho = V_4/V_3 = 1.2; 1.5; 2.0$

Note: $V_{1–4}$, $p_{1–4}$ are correspondingly volume (m^3) and pressure (Pa) of gas at the main points (1–4) of the cycle.

Analysis of the composition of burnt biogas showed that the most probable reason for the occurrence of dangerous components in exhaust gases after combustion may be highly-dispersed dust, falling into the burner together with the biogas stream whose concentration increases with the depth of sample collection. It is well known that dust particles with a highly

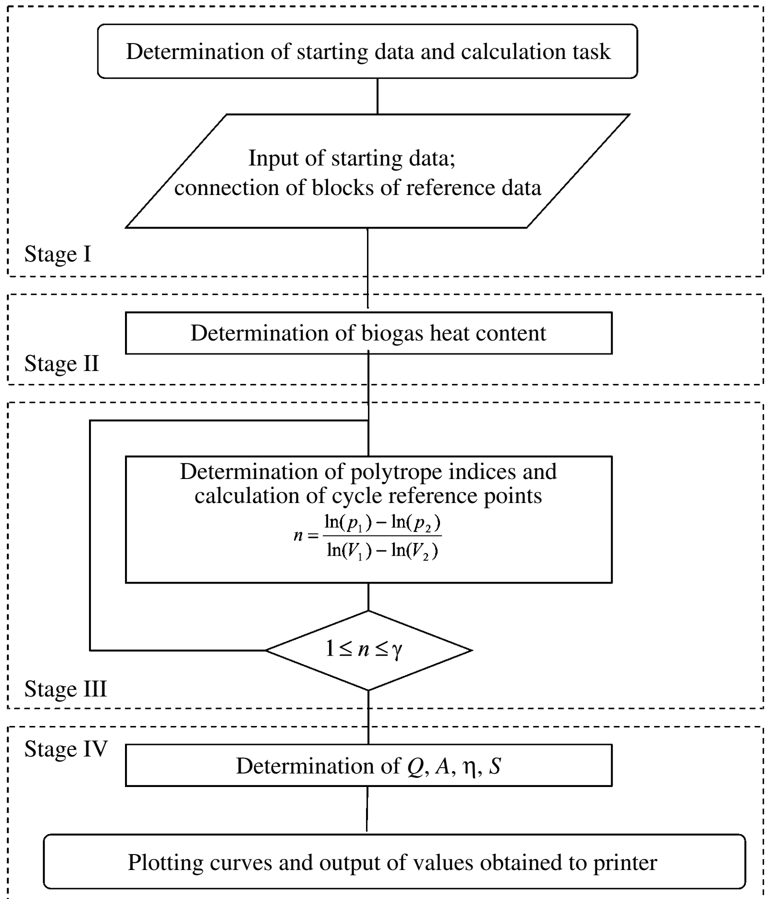

Fig. 1. Algorithm for calculating cycle parameters: p_1, p_2, V_1, V_2 are correspondingly pressure (Pa) and volume (m^3) in the first and second points of a polytrope; γ is adiabatic index; Q is the amount of heat supplied and extracted per cycle, W; A is work per cycle, J; η, S are cycle efficiency and entropy (J/(kg·K)).

developed surface are adsorbents. During their combustion, there is desorption and separation of absorbed compounds into the gas phase. Thus, in order to use biogas as an HE working medium it is necessary not only to dry and compress biogas before combustion [2], but also to clean exhaust gases from toxic gaseous compounds both before combustion (including from dust) and after it.

Results of thermodynamic calculations for a real biogas cycle were compared with results obtained for model methane–air–carbon dioxide gas mixtures according to the procedure for calculating parameters of a working medium (p, V, T) at characteristic points of the thermodynamic cycle, thermal efficiency and work completed by biogas per working cycle [3–5].

The main parameters (ε is degree of compression; ρ is the degree of preliminary expansion; λ is the degree of increase in pressure) are provided in Table 3. In calculations, it was considered that the composition and physicochemical properties of biogas as a working medium change with compression, therefore in each stage of the calculation the local adiabatic index was calculated and the whole process was considered to be polytropic. The excess air coefficient in calculations for each cycle was taken as 1.

As follows from Table 3, the cycle characteristics provided embrace the range of working parameters for almost all real HE. In this work for gas turbine plant (GTP) cycles, the change in the degree of preliminary expansion was also taken into account [6, 7].

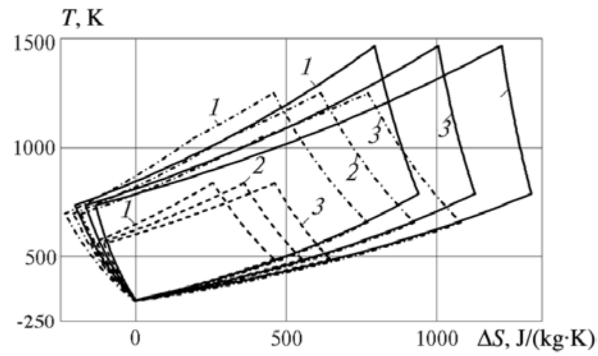

Fig. 2. T–ΔS-diagram of calculated cycles for model mixtures (CH_4–CO_2–air): – – –) Otto cycle; – · –) Trinkler cycle; ——) Diesel cycle; *1*) 30% CH_4; *2*) 50% CH_4; *3*) 70% CH_4.

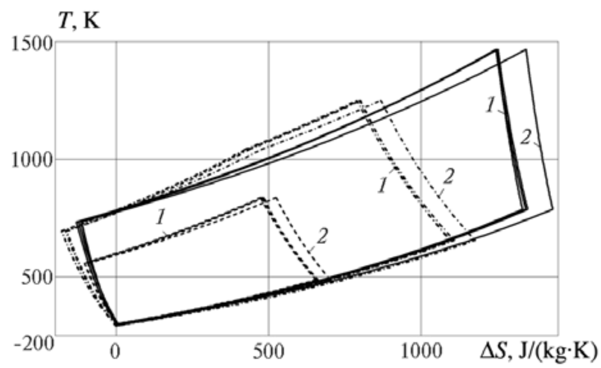

Fig. 3. T–ΔS-diagram of calculated cycles for a real biogas sample composition at a different collection depth (0.4, 1.0, 2.0, and 10 m): – – –) Otto cycle; – · –) Trinkler cycle; ——) Diesel cycle; *1*) $H = 0.4$ m; *2*) $H = 10$ m.

An algorithm for the calculation procedure for the main thermodynamic characteristics of the planned HE cycle for burning dump biogas (Fig. 1) was realized in MathCAD software [8]. According to the algorithm developed, in stage I there is choice of the type of thermodynamic cycle and input of starting data, and in stage II there is calculation of gas mixture heat content and determination of the adiabatic index $\gamma = c_p/c_v$ as the upper limit for the change in polytrope index. As an assumption, it is taken that biogas is stable in the original state, and it may be considered as an ideal gas mixture. Here the main mixture parameters are calculated according to the additive principle. In stage III, the polytrope index and working medium parameters at reference points of the cycle are calculated, and in stage IV cycle energy characteristics are determined and curves are plotted.

T–ΔS-diagrams are given in Fig. 2 for the Otto Diesel and Trinkler cycles in relation to the composition of a model gas mixture with respect to methane (30, 50, and 70%). Calculations showed that for a given working medium work that may be obtained in the Brighton cycle is so little that further consideration of this cycle is undesirable. It can be seen from Fig. 2 that most energy significant is the Diesel cycle. This is also confirmed by calculating the T–ΔS-diagram for cycles in a real biogas mixture composition (Fig. 3). The calculated results obtained also indicate that with an increase in methane concentration there is also an increase in useful work, produced by an HE per cycle, that may compensate losses in heating ballast admixtures in biogas. As follows from data in Fig. 2 the most energy preferable is the Diesel cycle since the area of the cycle,

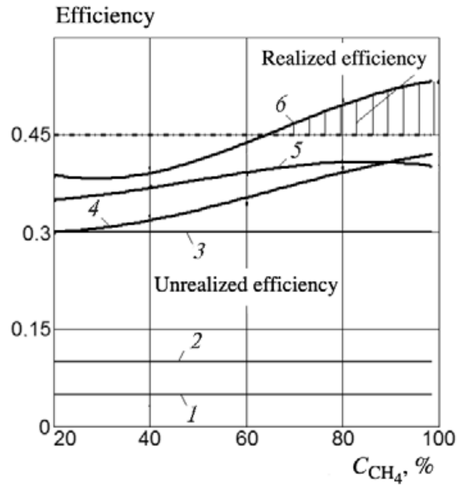

Fig. 4. Dependence of HE efficiency (taking account of technical and economic expenditure) and cycle thermodynamic efficiency on methane content C_{CH_4} in biogas: *1*) cleaning of biogas before combustion; *2*) biogas compression to 1.2 Pa before combustion; *3*) drying of biogas before combustion and cleaning after combustion; *4*, *5*, *6*) Otto, Trinkler, and Diesel cycle, respectively; – · –) overall ecological measures.

and this means the useful work within it, exceeds the same parameters for other cycles. A similar result has been obtained in comparative calculations for cycle parameters and T–ΔS-diagrams for biogas of real composition (see Fig. 3).

On the basis of the results obtained, it is possible to confirm that an HE ecological safety working on biogas is determined by the difference between cycle useful work and the expenditure in collection and pumping of biogas through an extended dump pipe system, in biogas compression during pumping into a damping gas holder, drying biogas from moisture, cleaning biogas from dust and cleaning waste gases from standard components to permissible discharge concentrations,. Results of calculations are provided in Fig. 4.

It follows from analysis of data in Fig. 4 that with observation of all production and nature protection operations useful work may be obtained with the use of biogas as a working medium only in a Diesel cycle with a methane content not less than 70%.

In this case, if for energy utilization of biogas in a SDW dump, for example by a GTP, it is possible with considerable probability to confirm that obtaining energy is possible either as a result of disrupting biogas operation technology for combustion, which leads primarily to a reduction in equipment life, or as a result of infringing standards for discharging toxic compounds into the atmosphere for exhaust gases.

Thus, the most ecologically safe installation for energy utilization of dump biogas is an HE operating on a Diesel cycle (the region of rational parameters for installations with respect to thermal utilization of biogas in dumps for burying SDW is shown by a broken-dotted line in Fig. 4). When using of the results of this work for practical purposes, it is necessary to consider that the thermodynamic efficiency of any HE cycle is its upper limit, and therefore the region of rational use of these installations is markedly lower.

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